

**LITHOSPHERIC BUCKLING AND INTRA-ARC
STRESSES:
A MECHANISM FOR ARC SEGMENTATION**

Final Report

NASA/ASEE Summer Faculty Fellowship Program--1988

Johnson Space Center

Prepared By:	Kerri L. Nelson
Academic Rank:	Lecturer
University and Department:	Sul Ross State University Analytical Laboratory Alpine, TX 79832
NASA/JSC	
Directorate:	Space and Life Sciences
Division:	Solar System Exploration
Branch:	Space Shuttle Earth Observation Office
JSC Colleague:	Charles A. Wood, PhD.
Date Submitted:	August 19, 1988
Contract Number:	NGT 44-005-803

ABSTRACT

Modern arcs have been subdivided into distinct segments based on features such as changes in the alignment of arc volcanoes, variations in seismic parameters (e.g. frequency, magnitude and distribution of earthquakes) and/or variations in arc lava chemistry. Models for segmentation are varied and include subduction of discontinuities on the ocean floor (transforms; ridges) and weaknesses in the overriding plate. However, these models are not generally applicable between or even within a given arc. Our investigation of 9 ocean-continent convergent margins has shown, however, that there are consistent patterns to segment development. Segments tend to form in 100-300 km lengths regardless of tectonic parameters such as convergence rate or subduction of ocean-floor features. Further, there are consistent relationships between the distribution of calderas in an arc and segment configuration: calderas are concentrated at segment margins and decrease in both size and number towards segment interiors. We model arc segmentation in terms of intra-arc stresses caused by buckling of the downgoing slab as it is subducted. Deformation and/or tearing of the subducted lithosphere induced by buckling provides sites for upwelling of asthenospheric material. As the asthenospheric material underplates the overriding slab, crustal thinning and extension occur, favoring the emplacement of caldera-forming magma chambers. Additionally, the large volumes and short residence times of magmas produced at these points precludes extensive modification of their chemistry by petrogenetic processes (e.g. fractionation, replenishment, assimilation and/or mixing) that are believed to be important in the evolution of more normal "arc-type" calcalkaline compositions such as those found at segment interiors.

INTRODUCTION

Volcanic arcs are often broken into discrete segments which are recognized by 1) changes in the volcanic front, 2) seismological data and/or 3) variations in chemistry along the arc (Stoiber and Carr, 1973; Issacks and Barazangi, 1977; Hughes et al., 1980). Although the presence of segments is well documented in individual arcs, little work has been done in the systematic comparison of segments among a number of arcs to determine what process(es) is (are) controlling the formation of segments within an arc. Factors such as discontinuities in the subducted slab, subduction of aseismic ridges, and/or crustal weaknesses have been invoked by a number of individuals to explain segmentation of given arcs (e.g. Issacks and Barazangi, 1977; Carr, 1984; Kay et al., 1982; Hall and Wood, 1985). To better delineate what factors are involved in segment development, we have evaluated segments from a number of arcs, using both a tectonic and volcanic perspective.

INVESTIGATIONS

Using data from the literature, we compiled a list of pertinent tectonic and volcanic parameters for each arc. The majority of the tectonic data was obtained from Jarrad's (1986) comparison of stresses at convergent margins. To minimize the number of variables influencing segment development, we chose arcs which had been active for at least 10 ma and were characterized by an oceanic plate being subducted beneath a continental plate. Arcs that satisfied these requirements were the Aegean, Ryuku, Central America, the Alaska Peninsula, Cascades, Japan, Kamchatka, Mainland Alaska, and the Central Andes. We were particularly interested in the relationship between stratovolcanoes and calderas within a segment as these volcanic features represent sites of focused magmatism and form in response to differing tectonic stresses (Hildreth, 1981; Nelson and Wood, 1987).

Using the volcanic data base, we noted the size and location of each caldera and stratovolcano for each arc. After plotting the volcanic data on maps, we determined the volcano/caldera distribution, and located the individual segments within an arc based solely on changes in strike of the volcanic front. As mentioned earlier, several criteria have been used to identify arc segments. While use of seismology and chemical data may be useful in refining segment boundaries in arcs, Issacks and Barazangi (1977) noted that the alignment of volcanoes within an arc best defines the individual segments. Further, the alignment of volcanoes is preserved long after subduction ceases, thus providing information on segmentation on

inactive and ancient arcs. This method may also be used where chemical data is insufficient to document geochemically anomalous volcanoes and calderas.

After establishing segments within each arc, we concentrated on isolating factors which may control segment location/formation. It became clear that there was no consistent relationship between location of segment boundaries and subduction of seafloor features. In fact, at the location of segment boundaries, there were no ocean floor features currently being subducted which could be called upon to cause segmentation. This does not preclude previous subduction of ridges, seamounts, transforms etc. which may have initiated earlier segmentation of an arc. However, subduction of such features has been called upon to alternatively focus (Hall and Wood, 1985), terminate (e.g. Issacks and Barazangi, 1977) or have no affect (e.g. Fisher et al., 1981) on volcanism and/or segmentation in an arc. Therefore, while subduction of seafloor features may be important in facilitating segmentation of some arcs, we do not believe it is a prerequisite to segmentation of all arcs.

Tectonic parameters which relate the interrelationship between both the subducting and overriding plate such as convergence rate and strain class were initially considered to be important in controlling the segmentation history of an arc. Strain class (SC) is a quantitative measure of the amount of extension or compression an arc is undergoing, with larger values for SC indicating a more strongly compressive arc. Intuitively, it would seem that the larger the magnitude of interaction between the two plates (e.g. faster convergence, higher SC values) the greater the number of segments that should form. This relationship is clearly not supported by our data set. In fact, the poor correlations observed for the number of segments vs. strain class ($r^2 = 0.344$; Figure 1) and convergence rate

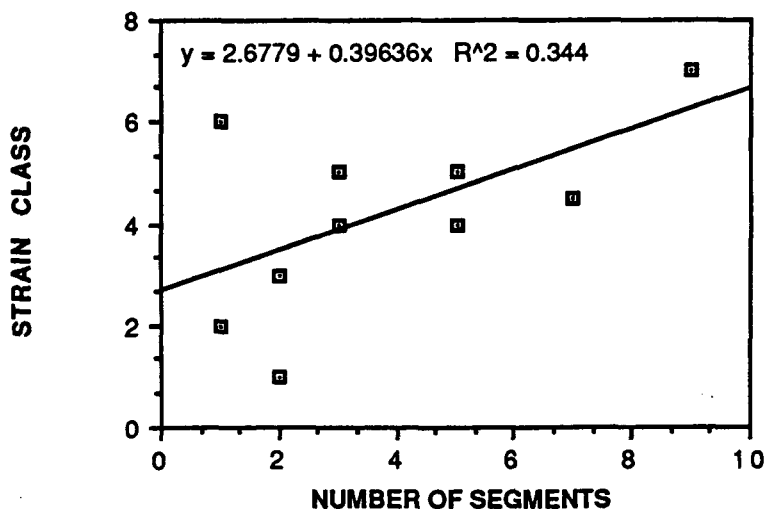


Figure 1.- The variation between number of segments and strain class.factors

($r^2 = 0.048$; Figure 2) would suggest that plate interactions are not primary factors in segmentation. Not only is segment number not controlled by SC,

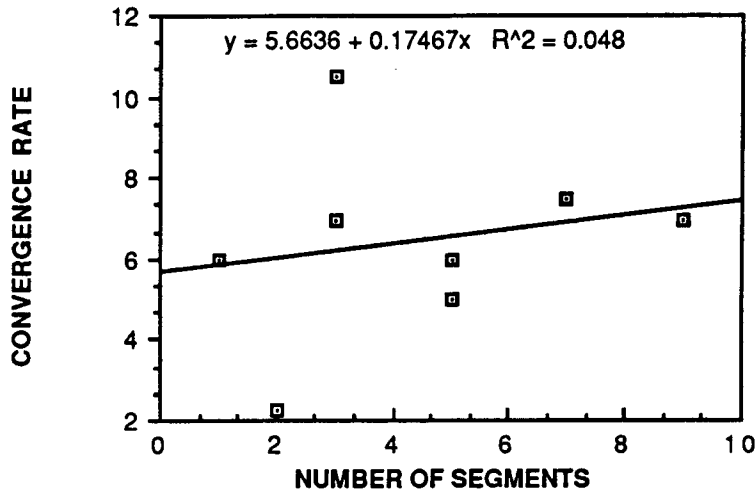


Figure 2.- Variation between segment number and convergence rate.

segment length is also independent of arc stress. Figure 3 illustrates that there is no systematic change in segment length with SC. Although SC 2 is unusual as it is represented by only one arc (Ryuku) which has only one defined segment, there is no clear relationship between SC and segment length: more extensional arcs do not form longer or shorter segments than compressional arcs. Most segments tend to form in lengths between 100 and 300 km (figure 4). This is the same range

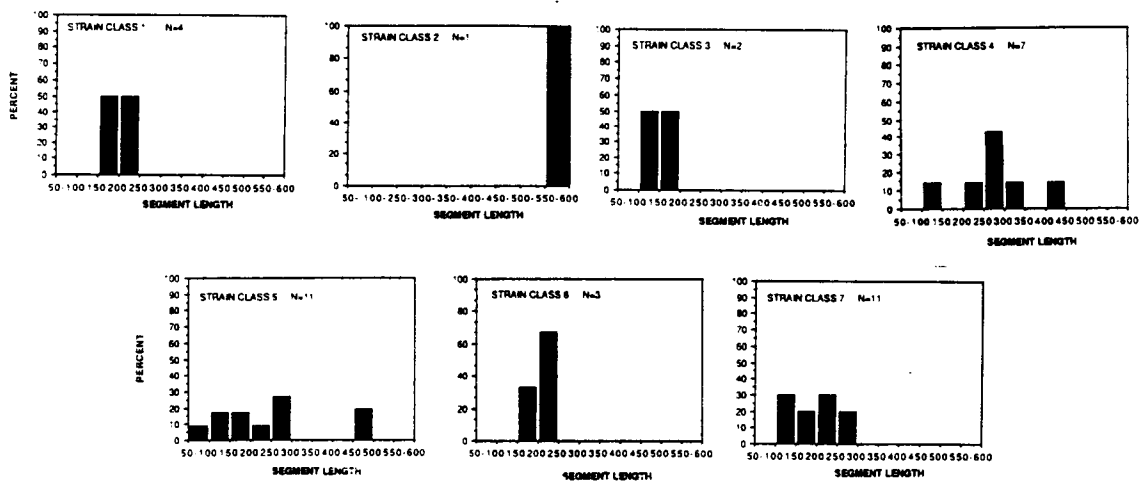


Figure 3.- Distribution of segment lengths as a function of strain class.

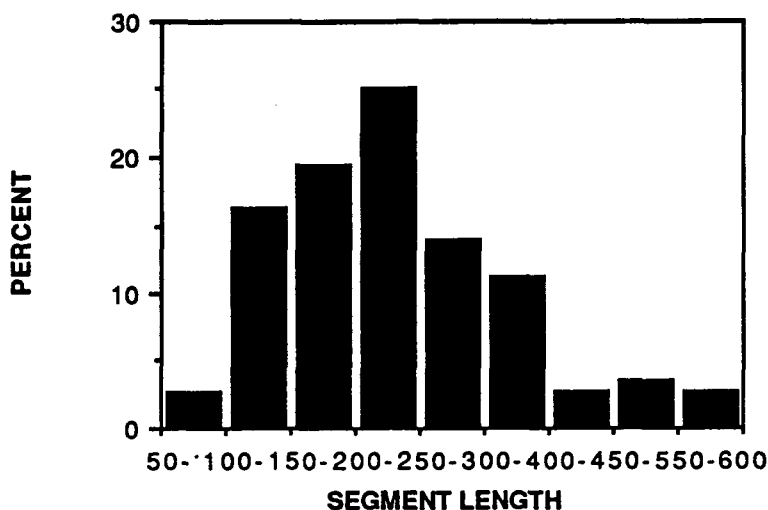


Figure 4.- Frequency of segment lengths.

that has been noted for individual arcs such as Middle America (Stoiber and Carr, 1973) and the Eastern Aleutians (Kienle and Swanson, 1983), indicating that segment length is relatively constant among arcs.

Other factors suggested as important in controlling segments are arc age and crustal thickness. Again, however, the relationship between these factors and segment development is not clear. The poor correlation between number of segments and arc age ($r^2=0.197$; Figure 5) indicates the segmentation history of an arc is not affected by maturity of an arc. In fact, it would seem that segmentation is established early in the history of an arc and is maintained throughout its development. There is a moderate correlation between crustal thickness and segment number ($r^2=0.621$; Figure 6) which may indicate that thicker crust may be weakened (fractured ?) by subduction and serve to more effectively segment an arc. However, careful examination of this relationship reveals that arcs with an average crustal thickness of 35-40 km can support between 1 and 7 segments. Clearly, crustal thickness is not a sensitive control or monitor of segmentation. Our statistical analysis (both correlation and stepwise regression) of the available data indicate that the dominant control on the number of segments was neither tectonic style nor character of the overriding plate. Rather, arc length (hence lateral extent of the subducted slab) is the dominant factor in controlling the number of segments (Figure 7; $r^2=0.769$; Correlation coefficient = 0.877;). This, coupled with the earlier observation that segment

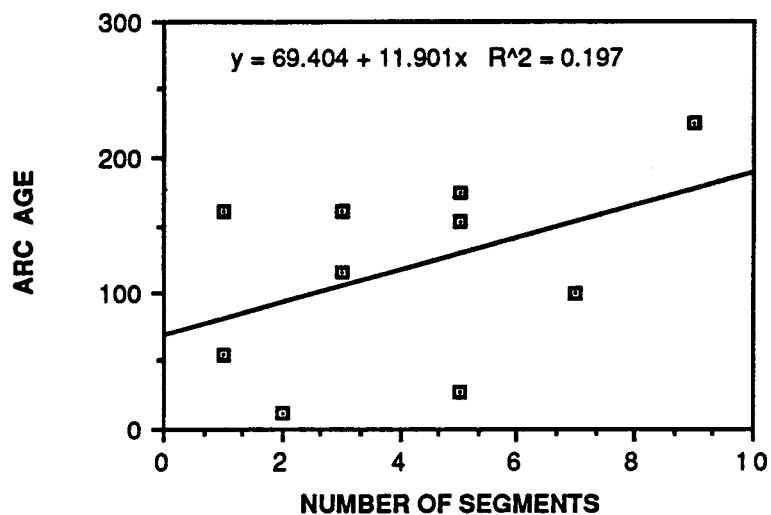


Figure 5.- Variation between segment number and arc age.

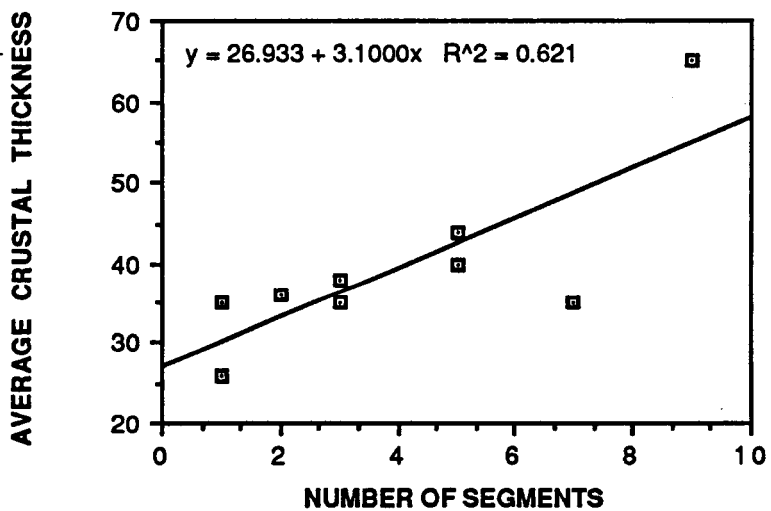


Figure 6.- Variation between segment number and average crustal thickness.

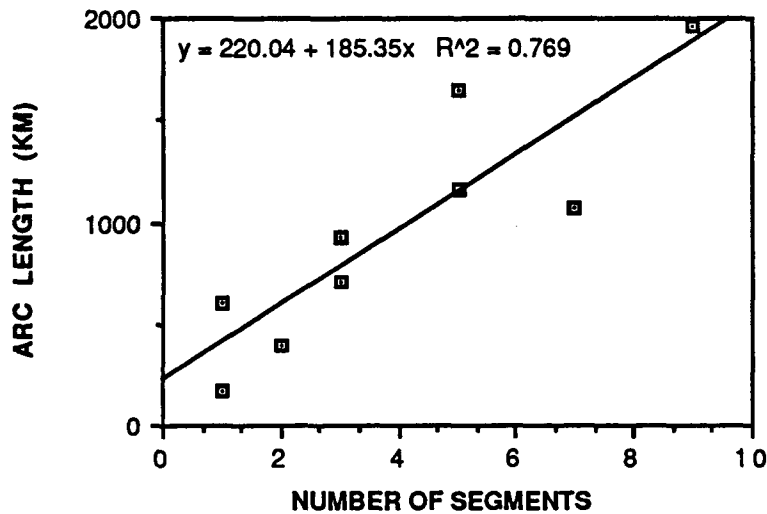


Figure 7.- Relationship between segment number and arc length.

lengths cluster at 100-300 km implies segmentation is characteristic of arcs and segment number is controlled by the horizontal extent of the downgoing slab.

As large-scale tectonic features are apparently not important in determining the length and number of segments in an arc, we next evaluated what small-scale (intrasegment) variations in stresses may be recorded in arcs. Hildreth (1981) noted that stratovolcanoes formed when extension was shallow and/or subordinate while calderas formed during crustal extension. Previously, we determined that caldera diameter reflected the amount of extension experienced in an arc: larger calderas formed as extensional stresses increased (Nelson and Wood, 1987). Therefore, examining the distribution of stratovolcanoes and calderas within segments should yield information on stress variations. To evaluate these variations, we divided each segment into percent lengths by effectively "folding" the segment in half: the geographic center of each segment was assigned a value of 50% length, and the percentage length decreased toward segment margins (0%). This allowed for easy comparison of segments of varying lengths. Some consistent relationships between calderas and percent segment length were observed. At segment boundaries, calderas can be located great distances behind the volcanic front while at segment interiors, they are located primarily on the front (Figure 8a). Also, the largest diameter calderas are located at segment boundaries and the diameter of calderas decreases toward segment interiors (Figure 8b). Finally, the highest percentage of calderas (38%) are located at segment boundaries and the percentage progressively decreases toward segment interiors (Figure 8c). These consistent relationships, which are seen for all 35 segments, argue for segment

boundaries being more extensional than segment interiors. Further, the relatively smooth decrease in both size and percentage of calderas from segment boundaries to interiors indicates that the change in stress along a segment are gradual and not abrupt as often implied.

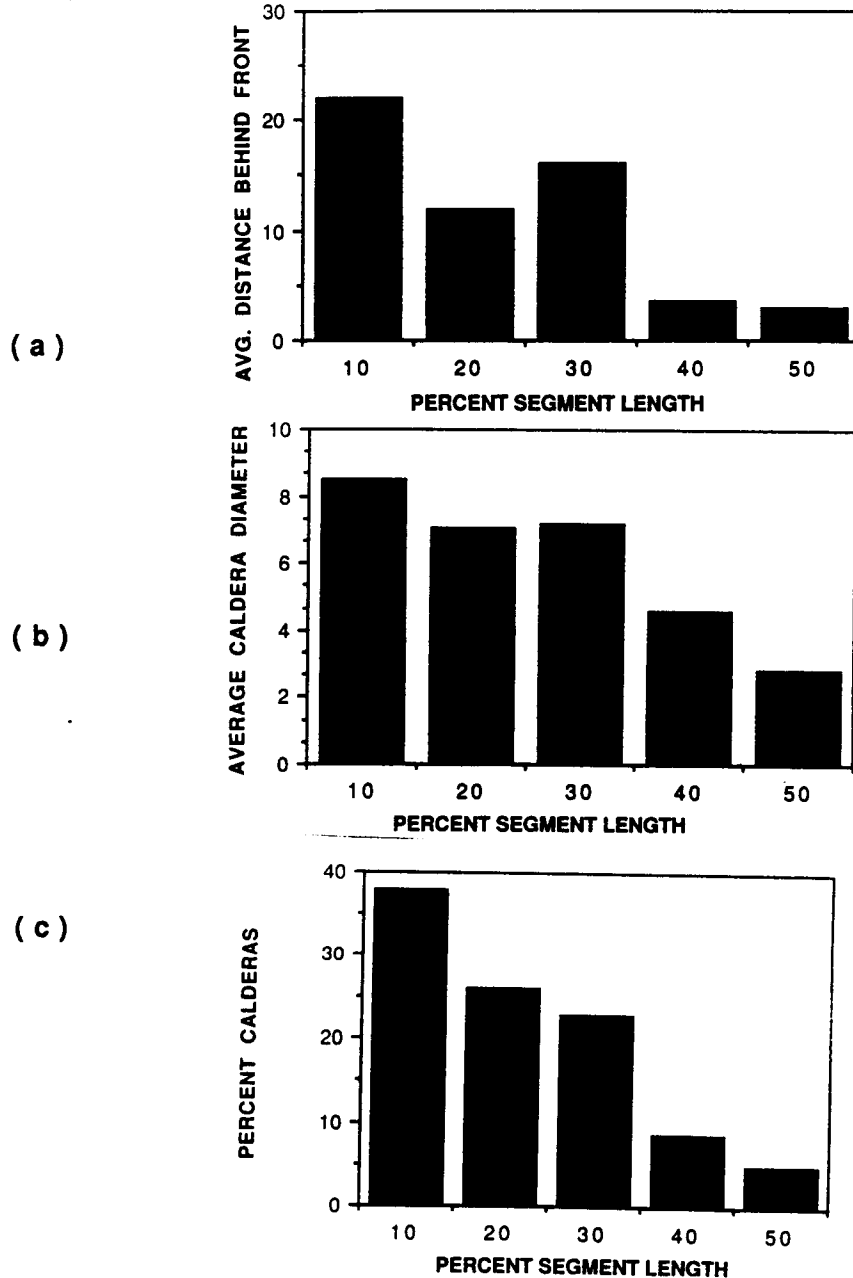


Figure 8.- Distribution of calderas within segments with respect to (a) distance behind the volcanic front; (b) caldera diameter and (c) percentage calderas.

SEGMENTATION MODEL

The similarity of segment development in length, number and stresses among the various arcs investigated is compelling evidence for a common process or processes controlling arc segmentation. We model segmentation as occurring in response to subduction of a spherical oceanic lithosphere beneath an overriding plate. Frank (1968) was first to note that the subduction processes should be influenced by the spherical nature of the subducted lithosphere and Strobach (1973) noted that there was a relationship between the curvature of the trench and the shape of the subducted lithosphere. Bayly (1982) suggested that the arcuate nature of volcanic chains in convergent margins could be produced by buckling of the lithosphere as it was subducted. Experimental modeling of lithospheric buckling reported by Yamaoka et al. (1986; 1987) and Yamaoka (1988) on an arc-arc scale has determined that the subducted lithosphere will deform through processes of buckling, with the wavelength of buckling corresponding to one arc length. Overall, the experimental models predicted the behavior of modern arcs fairly well. Interestingly, however, Yamaoka et al. (1987) noted that, for two arcs, the Aleutians and Middle America, the data achieved a better fit to experimental predictions after being subdivided (segmented?) into separate arcs.

We believe this large-scale (arc-arc) buckling is applicable to, and provides a mechanism for, small-scale (segment-segment) features observed within an arc. As the lithosphere is subducted, it will buckle, creating sites of inflection and/or tearing in the downgoing slab (Figure 9). Once deformed, portions of the slab can act independently of one another, descending at different rates and dips into the mantle with the overlying volcanic chain reflecting the changing geometry of the subducted model. A similar model was suggested by Carr et al. (1982) to account for the transverse boundaries observed in Central America. Further, the points of inflection/tearing in the lithosphere can provide sites for asthenospheric upwelling. Underplating by asthenospheric material at segment margins results in crustal thinning and extension, favoring the emplacement of large caldera-forming magma chambers at relatively shallow levels. The heat source for the crustal thinning/extension would decrease in intensity away from segment margins. Therefore, the distribution of calderas and stratovolcanoes within a segment is a natural consequence of buckling of the subducted slab.

It would seem, then, that lithospheric buckling can explain both the segmented nature of arcs and the distribution of calderas and stratovolcanoes within segments. Additionally, buckling provides a mechanism for explaining the observed chemical variations along segments. Several individuals (e.g. Hughes et al., 1980; Kay et

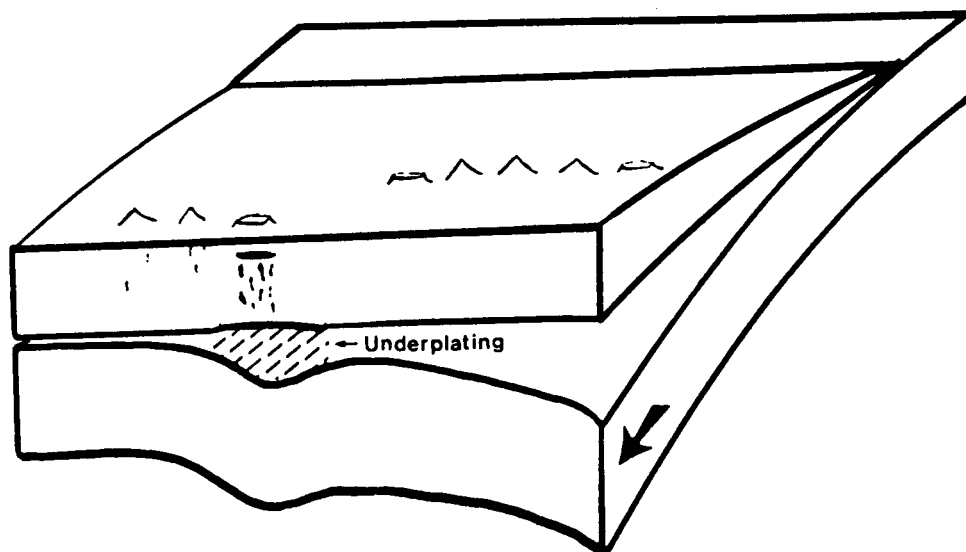


Figure 9.- Schematic model illustrating the relationship between lithospheric buckling and segmentation.

al., 1982; Carr et al., 1982; Wood and Moberger, 1983) have noted the calderas and volcanoes located at segment boundaries erupt material that tends to be chemically atypical for a given arc. Kay et al. (1982) modeled the chemical distribution (calc-alkaline vs. tholeiitic) observed for Aleutian Arc magmas as a function of segment boundary magmas (large tholeiitic centers) rising more quickly through the lithosphere than those magmas (calc-alkaline trend) which were located at segment interiors. Their general model of ascent rate affecting the chemistry of Aleutian magmas has implications for magma evolution at other arcs and can be accommodated within the framework of lithospheric buckling.

As mentioned earlier, points of tearing or inflection produced by lithospheric buckling would create more extensional environments. This is recorded by the presence of large calderas (e.g. Fisher et al., 1981; Carr, 1984; this study) and in the transverse alignment of volcanic cones (e.g. Carr et al., 1982) at segment boundaries. Extensional environments such as segment boundaries, would favor the rapid ascent of magma to shallow crustal levels. In contrast, magmas produced at the more compressional segment interiors would ascend more slowly. The differences in crustal residence times for magmas produced in these two environments is an important control on their chemical evolution.

Magmas produced in compressional environments are envisioned to pool, perhaps several times at different crustal levels, prior to eruption. In these chambers, the magmas will have ample opportunity to undergo processes of fractionation, replenishment, mixing and assimilation. These combined processes will produce the more typical range of arc-type magma chemistry associated with convergent margins. At segment margins, where significant amounts of subcrustal heating occurs in response to underplating of asthenospheric material, more voluminous magmas can be produced. Important in the evolution of these segment boundary magmas is their rapid rise through the crust. Although similar petrologic processes are operative throughout the segment (e.g. fractionation certainly can occur in segment boundary environments), the shorter crustal residence time and larger volumes of segment boundary magmas will place restrictions on the degree of chemical modification and evolution they can experience. As a result, they will tend not to have chemistries typical of arc magmas produced at segment interiors.. Rather than being chemically "anomalous", however, we believe that these segment boundary magmas are reflecting a normal tectonomagmatic processes at convergent margins which is produced by lithospheric buckling.

As a final point, Yamaoka et al. (1987) noted that the age and length of the subducted slab controlled the wavelength of lithospheric buckling. Further, Yamaoka (1988) noted that lithospheric bending is "strongly constrained by the lateral (along arc) continuation of the lithosphere". While we observed no correlation between age or length of the subducted slab, and segmentation history, our work on segmentation of modern arcs clearly indicates that the number of segments is controlled by the lateral extent of the subducted slab. As segment length is relatively constant (100-300 km) it would seem that segmentation should occur in all arcs, regardless of discontinuities on the subducting slab and/or crustal weaknesses. Features such as these may affect the distribution of segment lengths about the 100-300 km range and represent a second-order control on segmentation.

CONCLUSIONS

Comparison of segment development of a number of arcs has shown that consistent relationships between segmentation, volcanism and variable stresses exists. We have successfully modeled these relationships using the conceptual model of lithospheric buckling of Yamaoka et al. (1986; 1987). Lithospheric buckling (deformation) provides the needed mechanism to explain segmentation phenomenon: offsets in volcanic fronts, distribution of calderas within segments, variable segment stresses and the chemical diversity seen between segment boundary and segment interior magmas.

REFERENCES

- Bayly, B.: Geometry of Subducted Plates and Island Arcs viewed as a buckling problem. *Geology*, 1982, v. 10, pp. 179-191.
- Carr, M.J.: Symmetrical and Segmented Variation of physical and geochemical Characteristics of the Central American Volcanic Front. *J. Volcan. Geotherm. Res.*, v. 20, 1984, pp. 231-252.
- Carr, M.J.; Rose, W.I.; and Stoiber, R.E.: Central America. *Andesites*, R.S. Thorpe, ed., John Wiley and Sons, 1982, pp. 149-166.
- Fisher, M.A.; Bruns, T.R.; and Von Huene, R.: Transverse Tectonic Boundaries near Kodiak Island, Alaska. *Geol. Soc. America Bull.*, 1981, v. 92, pp. 10-18.
- Frank, F.C.: Curvature of Island Arcs. *Nature*, 1968, v. 220, p. 363.
- Hall, M.L.; and Wood, C.A.: Volcano-Tectonic Segmentation of the Northern Andes. *Geology*, v. 13, pp. 203-207.
- Hildreth, W.: Gradients in Silicic Magma Chambers: Implications for Lithospheric Magmatism. *J. Geophys. Res.*, 1981, v. 86, pp. 10153-10192.
- Hughes, J.M.; Stoiber, R.E.; and Carr, M.J.: Segmentation of the Cascade Volcanic Chain. *Geology*, v. 8, pp. 15-17.
- Issacks, B.L.; and Barazangi, M.: Geometry of Benioff Zones: Lateral Segmentation and Downward Bending of the Subducted Lithosphere. *Island Arcs, Deep Sea Trenches and Back-Arc Basins*, M. Talwani and W.C. Pitman, III, eds., *Am. Geophys. Union, Maurice Ewing Series I*, 1977, pp. 99-114.
- Jarrad, R.D.: Relations Among Subduction Parameters. *Rev. of Geophys.*, 1986, v. 24, pp. 217-284.
- Kay, S.M.; Kay, R.W.; and Citron, G.P.: Tectonic Controls on Tholeiitic and Calc-Alkaline Magmatism in the Aleutian Arc. *J. Geophys. Res.*, 1982, v. 89, pp. 4051-4072.
- Kienle, J.; and Swanson, S.E.: Volcanism in the Eastern Aleutian Arc: Late Quaternary and Holocene Centers, Tectonic Setting and Petrology. *J. Volcan. Geotherm. Res.*, 1983, v. 17, pp. 393-432.
- Nelson, K.L. ; and Wood, C.A.: Mid-Tertiary Volcano-Tectonic Development of the Southwestern Cordillera, North America. *EOS*, 1987, v. 68, p. 1532.
- Stoiber, R.E.; and Carr, M.J.: Quaternary Volcanic and Tectonic Segmentation of Central America. *Bull. Volcanol.*, 1973, v. 37, pp. 304-325.
- Strobach, K.: Curvature of Island Arcs and Plate Tectonics. *J. Geophys.*, 1973, v. 39, pp. 819-831.
- Yamaoka, K.: Spherical Shell Tectonics: on the Buckling of the Lithosphere at Subduction Zones. *Tectonophys.*, 1988, v. 147, pp. 179-181.

- Yamaoka, K.; Fukao, Y.; and Kumazawa, M.: Spherical Shell Tectonics and the Evolution of Subduction Zones. *Composition, Structure and Dynamics of the Lithosphere-Asthenosphere System*, K. Fuchs and C. Froidevaux, eds., 1987, pp. 205-217.
- Yamaoka, K.; Fukao, Y.; and Kumazawa, M.: Spherical Shell Tectonics: Effect of Sphericity and inextensibility on the Geometry of the descending lithosphere. *Rev. of Geophys.*, 1986, v. 24, pp. 27-53.
- Wood, C.A.; and Moberger, D.: Segment length: A Tectonic Control on Arc Volcanism. *EOS*, v. 64, p. 845, 1983.